Open Access Journal

**Journal of Power Technologies 95 (Polish Energy Mix) (2015) 100–106**

journal homepage:papers.itc.pw.edu.pl

# Energy scenarios for Poland—a comparison of PRIMES and TIMES–PL modeling results

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## Abstract

The aim of this paper was to compare the results of energy scenarios, which were prepared using PRIMES and TIMES–PL energy models for Poland. Both models were designed for modeling the mid- and long-term development of the energy system. The paper briefly describes the PRIMES and TIMES methodology, explaining both the similarities and differences of approach in relation to modeling the power supply. Four scenarios were analyzed in this study: (i) PRIMES–REF, (ii) TSAP–REF, (iii) TIMES–REF, (iv) TIMES–NUC. Although these scenarios were elaborated with the use of different modeling tools, there are many analogies in the evolution of the Polish power system up to 2050. As a consequence of EU climate policy and rising carbon prices within the European Union's Emissions Trading System (ETS) we observe a fuel and technology switch towards less carbon intensive options in all scenarios. The comparison is most adequate with PRIMES–REF and TIMES–NUC due to them having the best match in modeling assumptions and input parameters. In both, electricity generation from solid fuel declines throughout the projection period. This decline is sharper before 2030 and stabilizes thereafter. The relative share of fuels in the electricity generation mix by 2050 differs little in both scenarios. Solid fuels constitute more than 45%. The biggest differences were found in gas, nuclear, wind and solar. The differences for nuclear, wind and solar can be explained by the system-wide constraints applied in TIMES–PL. Increased use of gas in PRIMES–REF is presumably more of a methodological nature. $CO_2$ emissions have a similar, decreasing trend, reaching ca. 45 Mt in 2050. In both scenarios ca. 39% of electricity generated in thermal power plants in 2050 comes from units equipped with Carbon Capture and Storage (CCS). The study confirmed the robustness of the TIMES–PL model and showed that it can be used to provide valuable insights contributing to the development of Polish energy policy.

*Keywords:* power system, modeling, energy security, TIMES–PL, PRIMES, Poland.

## 1. Introduction

In December 2013 the European Commission published a report entitled "EU to 2050" (EETT2050) [1] in which a new EU Reference Scenario 2013 was presented. This scenario serves as reference for assessing the impact of currently envisaged EU policy initiatives in the areas of energy, transport and climate. The main analytical tool used to prepare this report was the PRIMES model developed by the National Technical University of Athens. The report describes the main modeling assumptions and provides key results for each EU Member State. This created an opportunity to make a comparison for Poland between the results of the EETT2050 Reference scenario and national projections obtained with the use of the TIMES–PL model [2].

Both TIMES and PRIMES are modeling systems that find a market equilibrium solution for energy supply and demand. However, there are some methodological differences which are discussed below. Besides this, differences also exists in the so-called Reference Energy System (i.e. a representation of the configuration of the national energy system), which is more detailed and adjusted to Pol-

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ish conditions in relation to power generation in the case of TIMES–PL [3] but limited only to one country.
In the first part of the paper the selected input data for the scenarios is compared. Then, the modeling results are presented and discussed. The main objective of the study was to reveal the differences in the electricity generation mix between the scenarios, particularly with regard to fuel and technological structure and $CO_2$ emissions.

## 2. Research Methodology

This study compares the results of two energy-economic model generators: PRIMES and TIMES (quoted as models hereafter). The Price-Induced Market Equilibrium System (PRIMES) was developed by the Energy–Economy–Environment Modeling Laboratory (E3MLab) at the National Technical University of Athens [4]. The Integrated MARKAL–EFOM System (TIMES) was developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) [5]. In this paper we consider the TIMES–PL model designed for the Polish power sector.

### *2.1. Description of the modeling approaches*

Both models were designed for modeling the mid- and long-term development of the energy system. Since they are not econometric models, they are not suitable for energy forecasting but they are relevant for the exploration of possible energy futures based on scenario projections. Both models have been used in many projects (with different spatial scales and temporal resolutions) for governments, companies and other institutions [6–9].
PRIMES is composed of several modules, each one representing the behavior of a specific (or representative) agent, a demander and/or a supplier of energy. Based on the microeconomic foundation, PRIMES formulates separate objective functions per energy agent. These sectoral objective functions (e.g. utility, costs, profits, etc.) are then optimized. TIMES has a single mathematical programming objective to maximize the net total surplus (i.e. the sum of producer and consumer surplus) in order to satisfy the provision of energy services.
In this paper we focus on the evolution of the power sector. Taking a closer look at the construction of both models with regards to this sector only, reveals some similarities between the models. In both, the relevant objective function represents the total power system cost. The main equations include: energy and other commodity balances, capacity-activity constraints, reserve margins, etc. The main decision variables include: activity variables (e.g. production of electricity, fuel consumption, etc.), new capacity additions, energy flows, storage capacities, etc. They require an exogenous provision of electricity demand, which normally comes from their other submodels (e.g. households, industry, etc.). In order to compute a supply-demand equilibrium both models allow for self-adjustment of demand in reaction to the changes in electricity price in line with price elasticity. All energy technologies in the models are characterized by a number of technical and economic parameters including: unit costs of investment by technology, unit variable costs, unit fixed costs, efficiencies, emission factors, etc. Also other parameters need to be provided such as fuel prices and potentials, prices of $CO_2$ emission allowances under the European Trading System, costs and potential parameters for transportation and storage of captured $CO_2$, etc. In both models investment expenditures are transformed into streams of annual payments. It is also possible to take into account system-wide constraints, e.g. related to the environment, resources, technology and others.
There are differences between the models. In a multi-country system, PRIMES optimizes interconnector power flows. PRIMES also includes non-linear cost-supply curves for all types of fuels, as well as for renewable power sources, for CCS and for nuclear plant sites.

### *2.2. Description of the analyzed scenarios*

Four scenarios were analyzed in this study: (i) PRIMES–REF, (ii) TSAP–REF, (iii) TIMES–REF, (iv) TIMES–NUC. We named PRIMES–REF—the Reference Scenario 2013 prepared with the use of PRIMES-EU28 for the European Commission in 2013, the results of which were published in the EETT2050 Report. Not all of the country input data and results were disclosed in this report. Some additional data and results of PRIMES for Poland were presented in the TSAP–REF scenario. It should be mentioned that in order to perform a cost-benefit analysis of energy scenarios in relation to atmospheric pollution and health effects, the PRIMES model is coupled with the IIASA GAINS model [4, 10]. The TSAP–REF scenario corresponds to the scenario prepared with the use of GAINS for review of the EU Thematic Strategy on Air Pollution (TSAP) based on the PRIMES Reference Scenario 2013. Therefore, TSAP–REF should be consistent with PRIMES–REF. The other two scenarios are the outcomes of the TIMES–PL model. They were built to analyze the future coal supply for the Polish power sector in the time period up to 2050 [2]. The main difference between these two TIMES–PL scenarios is the ETS price evolution (the latter scenario assumes higher prices). Additionally, TIMES–REF assumes the possibility of building only three nuclear reactors in 2025, 2030 and 2035 with a total capacity equal to 4.5 GW. The TIMES–NUC scenario assumes, that starting from 2025 until the end of the modeling horizon, the nuclear capacity can be increased by 1.5 GW every 5 years. TIMES–NUC does not foresee any preferential support for nuclear power as the name of the scenario may suggest.

### 2.3. *Description of the Reference Energy System*

The PRIMES–REF and TSAP–REF scenarios analyzed in this paper were prepared with the use of a multi-regional model consisting of 28 EU Member States. Each country in PRIMES EU28 is further disaggregated into sectors, i.e. tertiary, residential, industry and other sub-models, such as power and steam generation, transport, as well as gas, biomass and hydrogen supply. In the standard model the demand variability for electricity and heat are represented by including an hourly resolution of load in two typical days (one for winter and one for summer). Data for typical days also include wind velocity and solar irradiance. In each country, existing thermal plants are aggregated into 72 different types. For EETT2050 report, simulations were run for the 2010...2050 time period with 5-year time steps.

The TIMES–REF and TIMES–NUC scenarios were prepared with the use of TIMES–PL. TIMES–PL is the name of the model of the Polish power system generated with the use of TIMES [11]. It was developed at the AGH Faculty of Energy and Fuels. At present, it covers mainly electricity and heat supply. It includes all existing power plants as well as combined heat and power plants (CHPs). Each thermal power plant is represented in the model separately. Also, each gas fired combined heat and power plant is represented individually. Other existing power plants and CHPs are aggregated into main types according to the fuel/resource used (e.g. solar) and eventually the type of turbine installed (condensing or back pressure). Additionally, 25 main types of new power plants are available. For both TIMES–PL scenarios, simulations were run for the 2011...2050 time period with 5-year time steps. Each modeling year was split into 224 time slices in order to improve the temporal characteristics of both demand and supply sides (in the latter case this is particularly related to the increasing share of intermittent renewable technologies) [12]. The variability of electricity generation in wind turbines and solar photovoltaic (PV) was taken into account in each time slice. Electricity generation in wind turbines was based on the meteorological data for 2008 provided by the European Centre for Medium-range Weather Forecasting [13] for a location in the West Pomeranian Region (16.0°E i 54.1°N). Electricity generation in PV was calculated for the same location based on the data provided by Photovoltaic Geographical Information System [14].

### 2.4. *Description of the main assumptions*

Comparison of all modeling data and assumptions used for building the scenarios is impossible, as the data used in the PRIMES scenario was not fully disclosed. In this paper we compare two critical parameters which have a significant impact on the future shape of the electricity generation mix: (i) changes in the total gross electricity demand, and (ii) ETS carbon prices.

*Electricity Demand.* Future electricity demand constituted an exogenous input into TIMES–PL. It was estimated based on the method proposed in [15]. This method assumed convergence of the electricity intensity of the Polish economy (i.e. the ratio of the total final electricity consumption to Gross Domestic Product, which was 0.08 kWh/PLN in 2011) to the level determined by the least energy-intensive EU15 economies [2]. Determination of future electricity demand in PRIMES is more complex. In fact, PRIMES first projects useful energy demand (services provided by using energy or by saving energy) based on complex functional forms relating demand with macroeconomic drivers. Subsequently, final electricity consumption to meet energy needs is calculated.

It should be noted that in EETT2050 only the results of gross electricity generation are presented, whereas for TIMES–PL net electricity generation is reported. Therefore, the results of TIMES–PL were converted from net to gross values with the assumption that self-consumption of electricity in coal, nuclear, gas and other power plants is: 7, 4, 3 and 3% respectively [16]. The gross electricity generation is presented in Table 1. As the demand is the same for the pair of scenarios built with PRIMES and TIMES–PL, the results are provided only for the PRIMES–REF and TIMES–REF scenarios.

*ETS carbon prices.* The ETS carbon prices have a significant impact on the shape of the future fuel mix in coal-based countries, such as Poland [17]. For the PRIMES–REF scenario, ETS prices were endogenously derived so as to meet the $CO_2$ emission caps. The annual $CO_2$ emission caps were decreased each year starting from 2013 by 1.74% p.a. This resulted in the cumulative emission cap for the period from 2008 to 2050 being ca. 69.5 Gt. In contrast, ETS carbon prices constituted an exogenous input into TIMES–PL. Two pathways for the price evolution

Table 1: Gross electricity generation, TWh

| Scenario | 2010/2011 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| PRIMES–REF | 157.1 | 180.5 | 204.8 | 214.7 | 219.8 | 233.3 | 246.0 | 267.1 | 280.1 |
| TIMES–REF | 162.0 | 162.5 | 174.1 | 185.0 | 195.8 | 209.6 | 222.6 | 232.7 | 240.4 |

Table 2: Projections of ETS prices: 2015...2050, EUR/$t_{CO_2}$

| Scenario | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| PRIMES–REF | 5 | 10 | 14 | 35 | 57 | 78 | 89 | 100 |
| TSAP–REF | 5 | 10 | 14 | 35 | 57 | 78 | 89 | 100 |
| TIMES–REF | 10.0 | 15.0 | 15.0 | 17.0 | 18.0 | 18.9 | 19.9 | 21.1 |
| TIMES–NUC | 10.0 | 15.0 | 23.1 | 32.0 | 40.1 | 49.0 | 50.0 | 51.0 |

Table 3: Gross electricity generation by source (PRIMES–REF). Relative share, %

| Source/year | 2015 | 2030 | 2050 |
|---|---|---|---|
| Nuclear energy | 0.0 | 22.1 | 26.4 |
| Solids | 86.1 | 53.6 | 48.4 |
| Oil | 0.5 | 0.1 | 0.2 |
| Gas | 3.9 | 7.4 | 7.3 |
| Biomass | 5.2 | 6.5 | 7.4 |
| Hydro | 1.9 | 2.2 | 2.0 |
| Wind | 2.4 | 7.8 | 7.8 |
| Solar | 0.0 | 0.3 | 0.5 |

Table 4: Gross electricity generation by source (TIMES–REF). Relative share, %

| Source/year | 2015 | 2030 | 2050 |
|---|---|---|---|
| Nuclear energy | 0.0 | 0.0 | 0.0 |
| Solids | 82.9 | 69.9 | 66.7 |
| Oil | 1.8 | 1.5 | 1.2 |
| Gas | 3.3 | 2.4 | 1.4 |
| Biomass | 4.3 | 7.5 | 6.1 |
| Hydro | 1.8 | 1.6 | 1.6 |
| Wind | 5.9 | 17.4 | 19.0 |
| Solar | 0.0 | 0.0 | 4.0 |

Table 5: Gross electricity generation by source (TIMES–NUC). Relative share, %

| Source/year | 2015 | 2030 | 2050 |
|---|---|---|---|
| Nuclear energy | 0.0 | 6.3 | 20.6 |
| Solids | 82.9 | 63.2 | 46.6 |
| Oil | 1.8 | 1.5 | 1.2 |
| Gas | 3.3 | 2.4 | 0.7 |
| Biomass | 4.3 | 7.5 | 6.1 |
| Hydro | 1.8 | 1.7 | 1.6 |
| Wind | 5.9 | 17.4 | 19.1 |
| Solar | 0.0 | 0.0 | 4.0 |

were assumed. The first one, used in TIMES–REF, corresponded to the projection presented in [15]. The second one, used in TIMES–NUC, corresponded to the Current Policy Initiatives scenario, notably elaborated with the use of the PRIMES model, presented in [18]. Projections of ETS prices for all scenarios are presented in Table 2.

## 3. Results

We start our comparison of results with the fuel mix used for power generation. As presented in Table 1 there is a difference in overall gross electricity generation between the PRIMES–REF and TIMES–PL scenarios. Therefore, it is more suitable to compare the relative share of fuels used for power generation, which are depicted in Tables 3, 4 and 5.

As a result of, mainly, relatively low ETS prices used in TIMES–REF as compared to other scenarios (Tables 3, 4, and 5), the share of solids in the fuel mix remains at a high level, reaching ca. 67% in overall gross electricity generation. A lower ETS price does not provide a sufficient signal for investment in nuclear power. The assumed technology progress ratio for onshore wind and the resulting decrease of unit investment costs leads this technology to dominate the RES-based electricity generation. The TIMES–NUC scenario is more relevant for comparison with PRIMES–REF, as the ETS price difference is much lower. Only in the final decade starting from 2040 is a sharp increase in ETS prices observed in the PRIMES–REF scenario, elevating the $CO_2$ allowance price to 100 EUR/t by 2050. There is a faster fuel switch from solids to other fuels in PRIMES–REF as compared to TIMES–NUC, particularly to nuclear and gas. How-

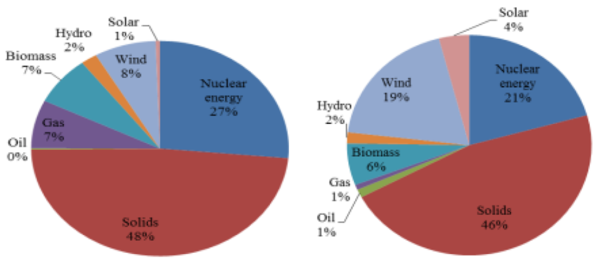


Figure 1: Gross electricity generation by source in 2050 for PRIMES–REF (left image) and TIMES–NUC(right image) scenarios

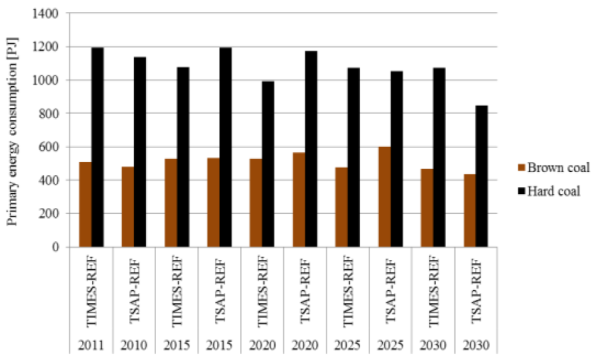


Figure 2: Primary energy consumption in power generation and district heating, PJ

ever, the electricity generation mix is not much different at the end of the modeling horizon, as depicted in Fig. 1. In both scenarios solids have a >45 % share in that year.

As shown in Fig. 1, the use of gas for power generation is marginal in the TIMES–REF scenario. This is mainly due to high gas prices as compared to other fuels [2]. In fact, this scenario does not assume a significant decrease in natural gas prices in the future. This situation may change, however, with successful exploration of domestic unconventional natural gas reserves [19]. The main indicators for electricity generation are presented in Table 6. The gross thermal power generation efficiency rises faster in PRIMES–REF and reaches almost 50% in 2050. In the TIMES–NUC scenario, the efficiency increase in the period after 2040 is halted by the slightly higher share of electricity generated in the power plants equipped with carbon capture and storage systems. In both scenarios electricity from CCS has a share of ca. 39% in overall electricity generation by 2050.

The comparison of primary energy consumption in the power generation and district heating sector, with a distinction between hard and brown coal, was only possible for the TSAP–REF scenario and for the 2010...2030 time period. The results are depicted in Fig. 2. The consumption of brown coal increases in both scenarios up to 2020 and falls in 2030 by 8% and 9% compared to the base year in TIMES–REF and PRIMES–REF, respectively.

Hard coal consumption decreases from ca. 1200 PJ in 2011 to ca. 990 PJ in 2020 and starts to increase afterwords to reach ca. 1070 PJ in 2030. The reverse trend is observed in the TSAP–REF scenario, in which hard coal consumption increases, peaking in 2015, and decreases afterwords to reach ca. 850 PJ in 2030. In this time period, the differences in results between

TIMES–REF and TIMES–NUC are very small and exist only after 2025.

A different electricity generation mix results in different $CO_2$ emissions, which are at their highest in the TIMES–REF scenario. In PRIMES–REF and TIMES–NUC the emissions have a similar, decreasing trend, reaching ca. 45 Mt in 2050 (Table 7).

## 4. Conclusions

The comparison of modeling results for the long term energy scenarios for Poland considered in this paper revealed many similarities. Although the analyzed scenarios were elaborated with the use of different modeling tools, i.e. PRIMES and TIMES–PL, there are many analogies in the evolution of the Polish power system up to 2050. As a consequence of EU climate policy and rising ETS carbon prices we observe a fuel and technology switch towards less carbon intensive options in all the scenarios. TIMES–NUC is more suitable for a comparison with PRIMES–REF than TIMES–REF, as the ETS price difference between them is much lower.

In general, electricity generation from solid fuel declines throughout the projection period. This decline is sharper in the period up to 2030 and stabilizes thereafter at the level of ca. 50%. Maintaining such a high share of electricity generated from solids is possible due to the installation of CCS systems. In both scenarios ca. 39% of electricity generated in thermal power plants in 2050 comes from units equipped with CCS.

The biggest differences in relative share of gross electricity generation were found with gas, nuclear, wind and solar. In 2050 the shares of gas and nuclear are higher in the PRIMES–REF scenario ca.: 6 and 6%, while wind and solar shares are lower by 11 and 3%, respectively. The differences in the use of nuclear, wind and solar can be explained by system-wide constraints related to RES and nuclear, which were imposed in TIMES–PL scenarios. It was assumed that the obligatory share of electricity generated from RES in the final net electricity consumption

Table 6: The main indicators for electricity generation in thermal power plants

| Indicator | Scenario | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Gross power generation efficiency, % | PRIMES–REF | 37.5 | 39.3 | 39.1 | 40.0 | 42.8 | 44.3 | 46.6 | 49.8 |
| | TIMES–NUC | 37.4 | 39.4 | 39.5 | 39.9 | 41.7 | 45.9 | 45.6 | 45.8 |
| Electricity from CCS, % | PRIMES–REF | 0.0 | 1.2 | 0.8 | 1.1 | 12.8 | 18.6 | 24.5 | 38.7 |
| | TIMES–NUC | 0.0 | 0.0 | 0.0 | 0.0 | 9.8 | 28.6 | 35.0 | 39.1 |

Table 7: $CO_2$ emissions from power generation and district heating, Mt

| Scenario | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| PRIMES–REF | 169.6 | 170.1 | 165.4 | 129.5 | 95.4 | 78.3 | 71.7 | 44.2 |
| PRIMES–REF | 167.2 | 158.7 | 160.5 | 159.7 | 161.8 | 154.7 | 151.0 | 149.2 |
| TIMES–NUC | 167.2 | 158.7 | 160.5 | 147.9 | 119.1 | 77.3 | 55.4 | 46.7 |

will be 35% in 2050. Initially, this drives electricity generation from wind. With the gradual harnessing of available wind potential and the lowering of unit investment costs of PV technologies due to learning and scale effects, electricity will see an increase from solar-based generation, mainly after 2040. The new capacity addition constraint prevents more investment in nuclear power. An increased use of gas in PRIMES–REF is presumably more of a methodological nature. In both scenarios gas plays mainly the role of a back-up technology for intermittent RES. Renewables have a very high share in power generation in the PRIMES–REF scenario at an EU level. However, RES use in Poland is even higher in TIMES–NUC. Therefore, there must be another explanation than simply balancing the fluctuating domestic RES-based electricity supply. The PRIMES–REF scenario assumes the completion of an internal EU electricity market and considerable investment in transmission grids. As PRIMES EU28 models interconnector power flows between countries, gas power plants can be used for balancing services for the entire EU system. Still, different technical assumptions may exist as regards operational flexibility of thermal power plants. One should also bear in mind that gas is less carbon intensive and higher ETS carbon prices are assumed in the PRIMES–REF scenario.

This paper places an emphasis on comparing the results of energy scenarios prepared using PRIMES and TIMES–PL energy models for Poland. The study confirmed the robustness of the TIMES- PL model and showed that it can be used to provide valuable insights that contribute to the development of Polish energy policy.

**Acknowledgments**

This work received financial support and was completed within the statutory funding of AGH (no. 11.11.210.217). It was also partially done within the framework of statutory research of the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences.

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